Physics With Large Underground Detectors

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Thanks for generous input to —

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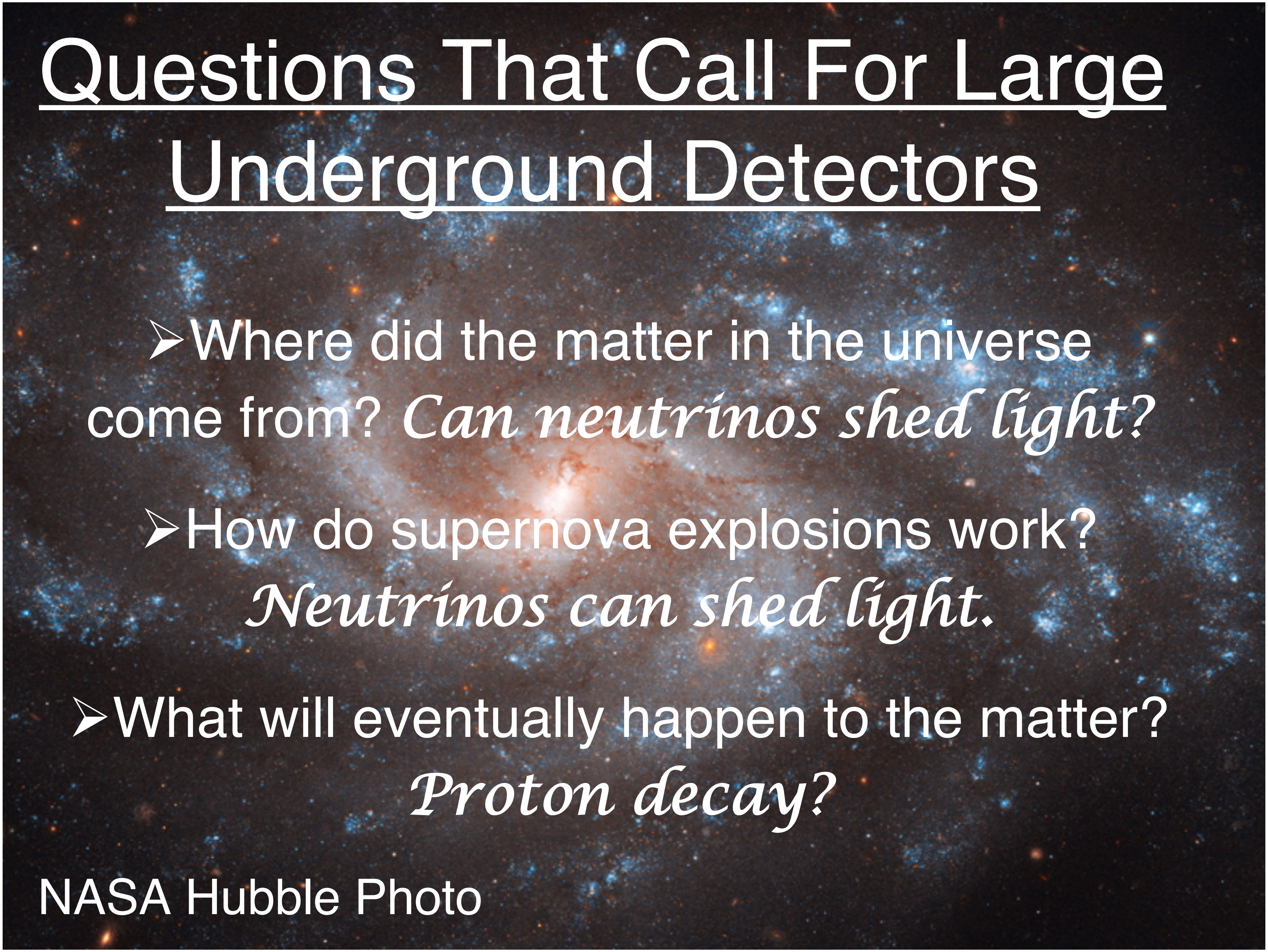


Questions That Call For Large Underground Detectors

➢Where did the matter in the universe come from? *Can neutrinos shed light?*

➢How do supernova explosions work? *Neutrinos can shed light.*

➢What will eventually happen to the matter? *Proton decay?*

NASA Hubble Photo

Neutrinos and the Origin of Matter

The Puzzle

Today: $B \equiv \#(\text{Baryons}) - \#(\text{Antibaryons}) \neq 0.$

Standard cosmology: Right after the Big Bang, $B = 0$.

Also, $L \equiv \#(\text{Leptons}) - \#(\text{Antileptons}) = 0.$

How did $B = 0 \Rightarrow B \neq 0$?

An appealing possible answer is **Leptogenesis**.

(Fukugita, Yanagida)

Leptogenesis is a very natural consequence of the **See-Saw** picture, the most popular explanation of why neutrinos are so light.

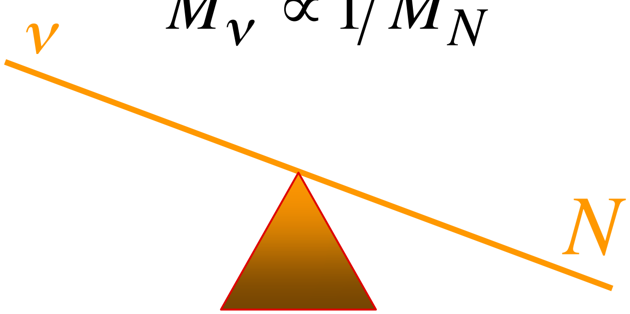
The straightforward See-Saw adds to the Standard Model (SM) 3 very ***heavy*** neutrinos N_i, $i = 1, 2, 3$, to match the 3 ***light*** lepton families $(\nu_\alpha, \ell_\alpha)$, $\alpha = e, \mu, \tau$.

The heavy neutrinos N_i are coupled to the rest of the world only through the Yukawa interaction —

$$\mathcal{L}_{\text{Yukawa}} = \underbrace{\overline{L}}_{\text{SM lepton doublets}}\,\underbrace{\overline{H}}_{\text{SM Higgs doublet}}\,\overbrace{y}^{\text{Yukawa coupling matrix}}N + h.c.$$

A consequence of this picture is —

$M_\nu \propto 1/M_N$



See-Saw Relation

{ *Yanagida;*
Gell-Mann, Ramond, Slansky;
Mohapatra, Senjanovic;
Minkowski }

Another consequence is that $\overline{N} = N$ and $\overline{\nu} = \nu$.

Leptogenesis is quite likely another consequence.

During the ***hot*** Big Bang, the N_i were made.

$\cancel{CP}$ phases in the matrix y would have lead to —

$$\Gamma\left(N \to \ell^- + H^+\right) \neq \Gamma\left(N \to \ell^+ + H^-\right)$$

and

$$\Gamma\left(N \to \nu + H^0\right) \neq \Gamma\left(N \to \overline{\nu} + \overline{H^0}\right)$$

This violates CP in the leptonic sector, and violates lepton number L.

Starting with a universe with $L = 0$, these decays would have produced one with $L \neq 0$.

The Standard-Model ***Sphaleron*** process, which does not conserve B or L, would then have converted some of this $L \neq 0$ into $B \neq 0$.

$$B_i = 0$$
$$L_i \neq 0$$

Initial state from N decays

→ Sphaleron Process →

$$B_f \cong -\frac{1}{3} L_i$$
$$L_f \cong \frac{2}{3} L_i \cong -2 B_f$$

Final state

During the ***hot*** Big Bang, the N_i were made.

~~CP~~ phases in the matrix y would have lead to —

$$\Gamma\left(N \to \ell^- + H^+\right) \neq \Gamma\left(N \to \ell^+ + H^-\right)$$

and

$$\Gamma\left(N \to \nu + H^0\right) \neq \Gamma\left(N \to \bar{\nu} + \overline{H^0}\right)$$

This violates CP in the leptonic sector, and violates lepton number L.

These are the key ingredients of Leptogenesis.

Starting with a universe with $L = 0$, these decays would have produced one with $L \neq 0$.

To establish that there is CP violation in the leptonic sector:

Show that there is CP violation in neutrino oscillation.

To establish that there is lepton number violation:

Show that neutrinoless double beta decay occurs.

Q: Don't we expect CP violation in neutrino oscillation, so finding it won't teach us anything?

A: Didn't we expect the leptonic mixing angles to be small?

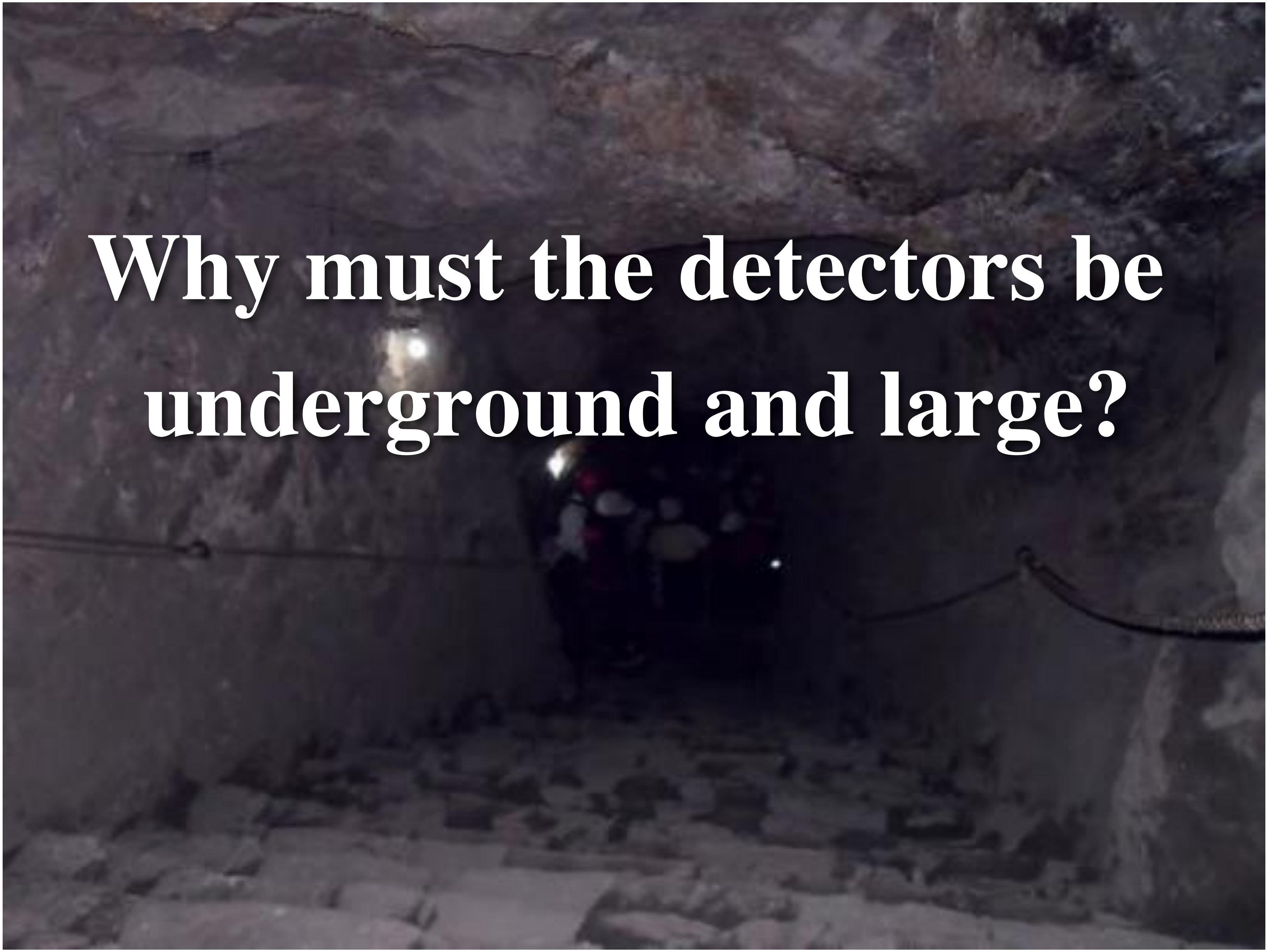
CP is a fundamental symmetry.

Is its nonconservation
special to quark mixing?

Or, does it occur in both
quark and lepton mixing,
as suggested by Grand Unified Theories,
which unify the quarks and the leptons?

Q: How precisely do we need to measure δ_{CP}?

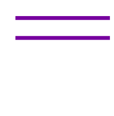
A: Neutrino parameters should be measured with precision mainly to look for physics beyond the 3 – neutrino paradigm.


Why must the detectors be
underground and large?

Going Underground

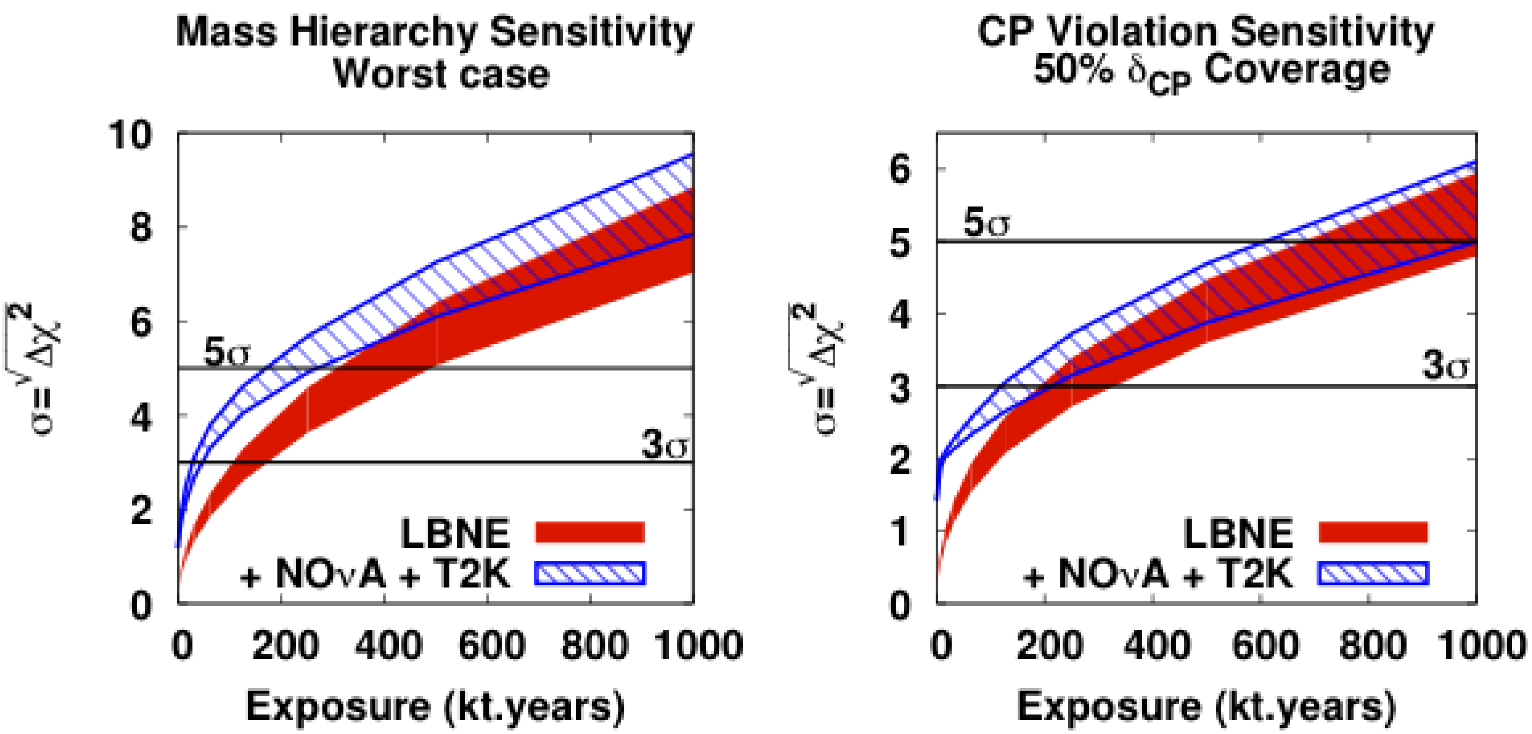
For neutrino beam physics,
safer with respect to background issues.

Underground, one can study the atmospheric neutrinos too, and use them to help determine the neutrino mass hierarchy.

An inverted hierarchy  would suggest a possible symmetry to explain the near degeneracy among the heavier neutrinos.

LBNE MH/CPV Sensitivities vs. Exposure

M. Bass, CSU (M. Bishai)



with LBNE ONLY + beam upgrades:

Need 100kt.yrs at 700kW to resolve MH with $\geq 3\sigma$ for all δ_{cp}

Need 200kt.yrs at 700kW to resolve CPV with $\geq 3\sigma$ for 50% δ_{cp}

Need 700kt.yrs at 700kW to resolve CPV with $\geq 5\sigma$ for 50% δ_{cp}

Studying Supernovae by Studying Their Neutrinos


(Raffelt)
Neutrinos from next nearby supernova:
A once-in-a-lifetime opportunity – don't miss it!

Neutrinos play a leading role in the dynamics of a core collapse supernova.

They carry away 99% of the emitted energy.

They probably re-energize the stalled outgoing shock.

They are also messengers from within the star with information on what is going on there.

We would like to study the time-dependence, energy spectrum, and flavor content of the neutrino flux.

Water Cerenkov and LAr Detectors Are Complementary

A water Cerenkov detector is sensitive to —

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

A LAr detector would be sensitive to —

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

This would give one sensitivity to the deleptonization neutrinos, coming from —

$$e^- + p \rightarrow \nu_e + n$$

The neutral-current process —

$$\nu_x + (A,Z) \to \nu_x + (A,Z)^*$$

$$(A,Z)^* \to (A,Z) + \gamma$$

would be sensitive to the total flux $\phi_{\nu_e} + \phi_{\nu_\mu} + \phi_{\nu_\tau}$.

Comparison with ϕ_{ν_e} would yield $\phi_{\nu_\mu} + \phi_{\nu_\tau}$.

Studying SN neutrinos on the surface may be possible with a LAr detector, but underground the background questions would be non-issues.

Adding detector mass allows the detector to study the neutrinos from more distant supernovae, thus increasing the chance of seeing at least one supernova.

Adding detector mass also allows more detailed study (e.g., getting the spectrum) of the neutrinos from a supernova at a given distance.

Proton Decay

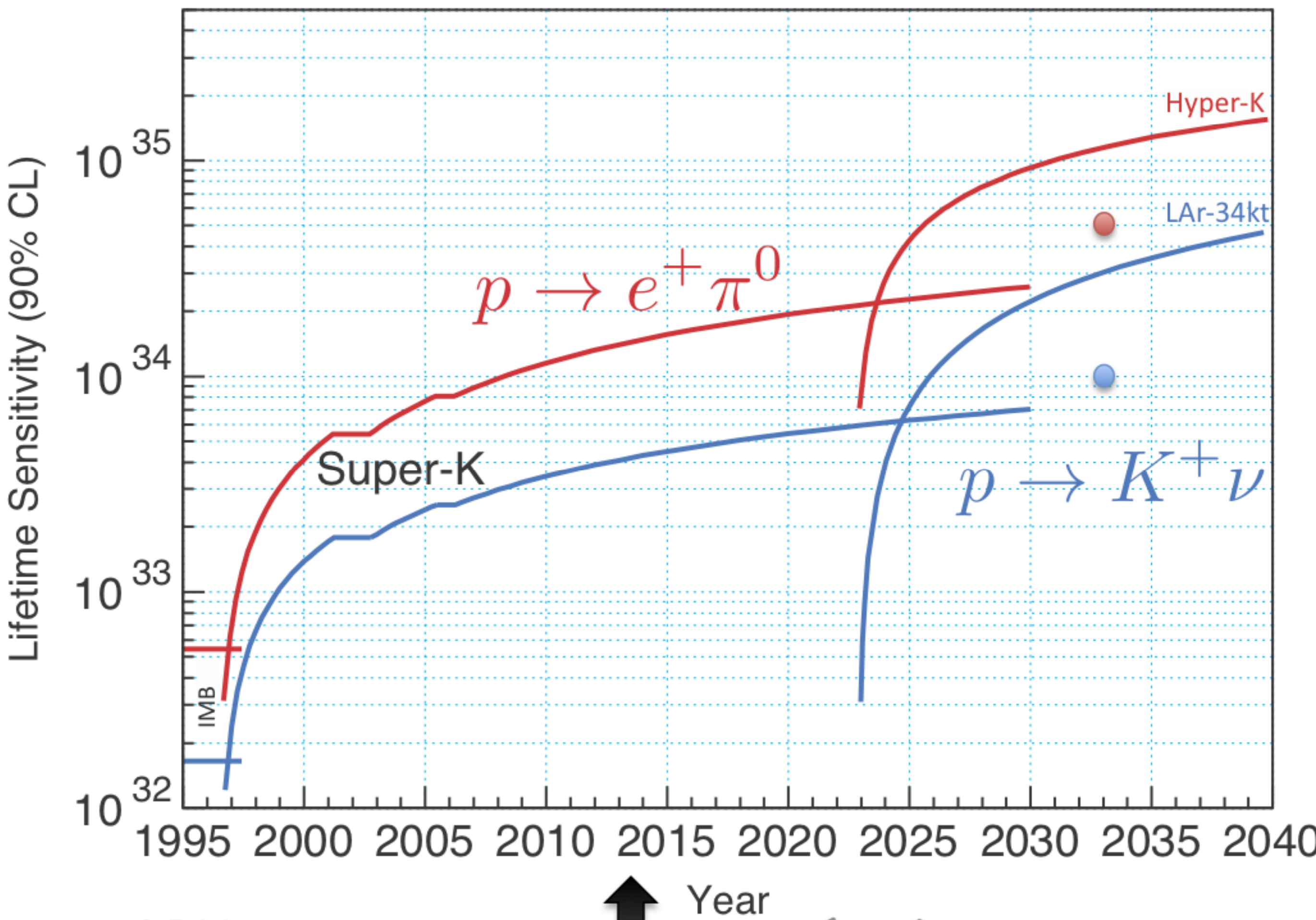
The discovery that the building blocks of atomic nuclei will eventually disappear would profoundly affect our view of the universe.

In addition, the discovery that protons decay, a signature prediction of Grand Unified Theories (GUTS), would be evidence in favor of this class of theories.

GUTS involve physics at a mass scale far beyond the reach of any foreseeable accelerator.

To search for proton decay, detectors must be underground to avoid backgrounds.

Proton Decay Search Territory



τ/B = 5e34
17 evts
1 BG

τ/B = 1e34
9 evts
0.3 BG

10 year sample points

~ 0.5 Mt yr exposure by Super-K before next generation experiments

now

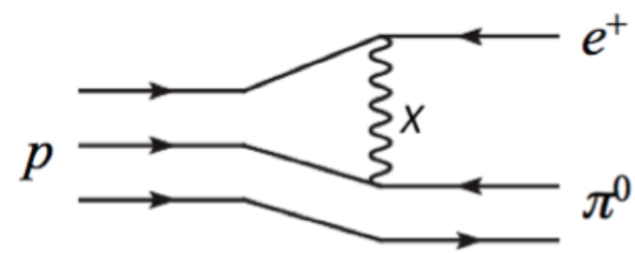
Starting time? Guess 1 decade from now.
Adjust starting time as you wish.

(Kearns)

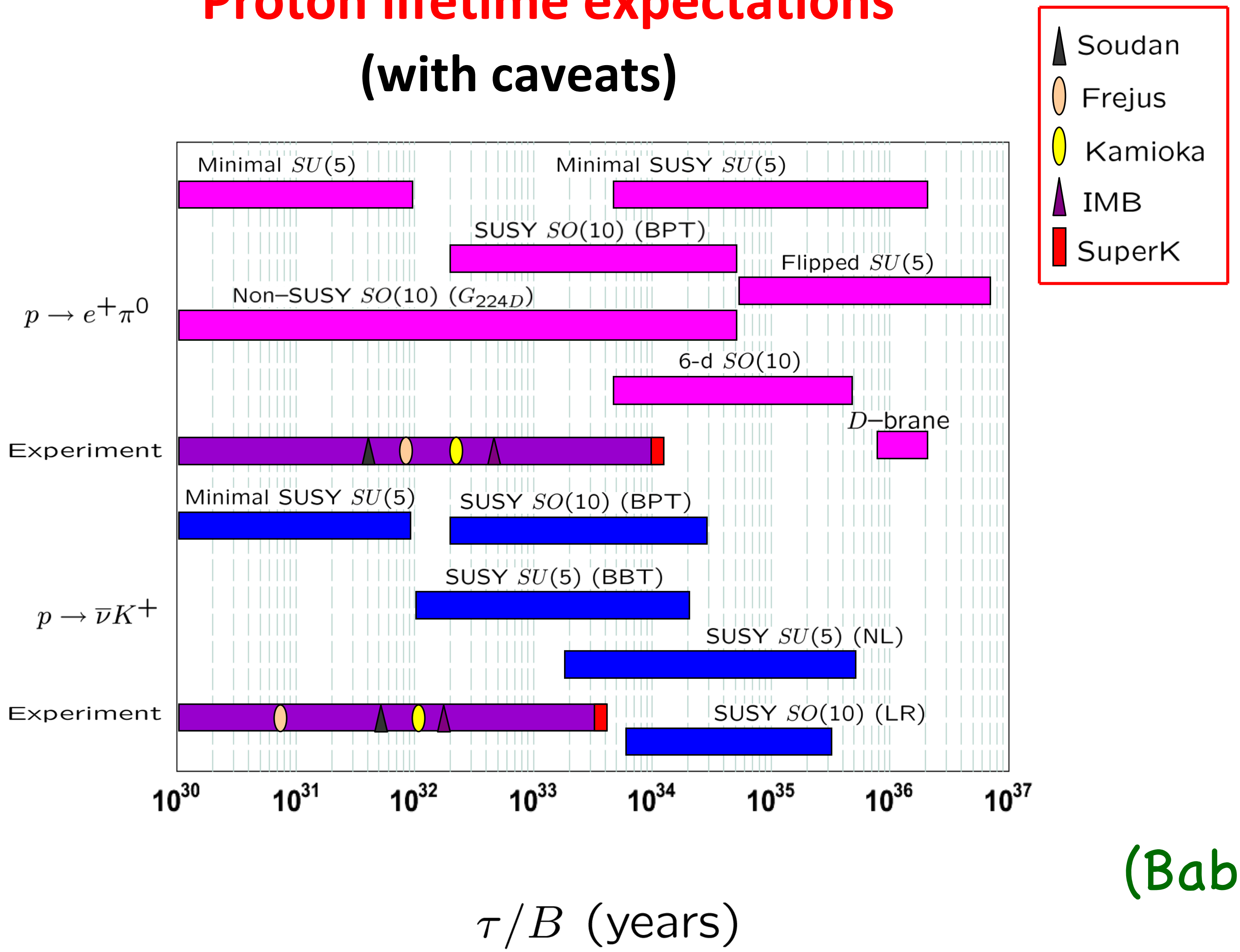
For each decay mode, do GUTS lead us to expect τ/B in the accessible range ?

Coupling constant extrapolations from present energies suggest a Grand Unification scale of ~ 2 x 10^{16} GeV.

Proton decay can be caused by exchange of a heavy boson X with mass somewhat below this scale. $\tau \propto m_X{}^4$, thus uncertain.

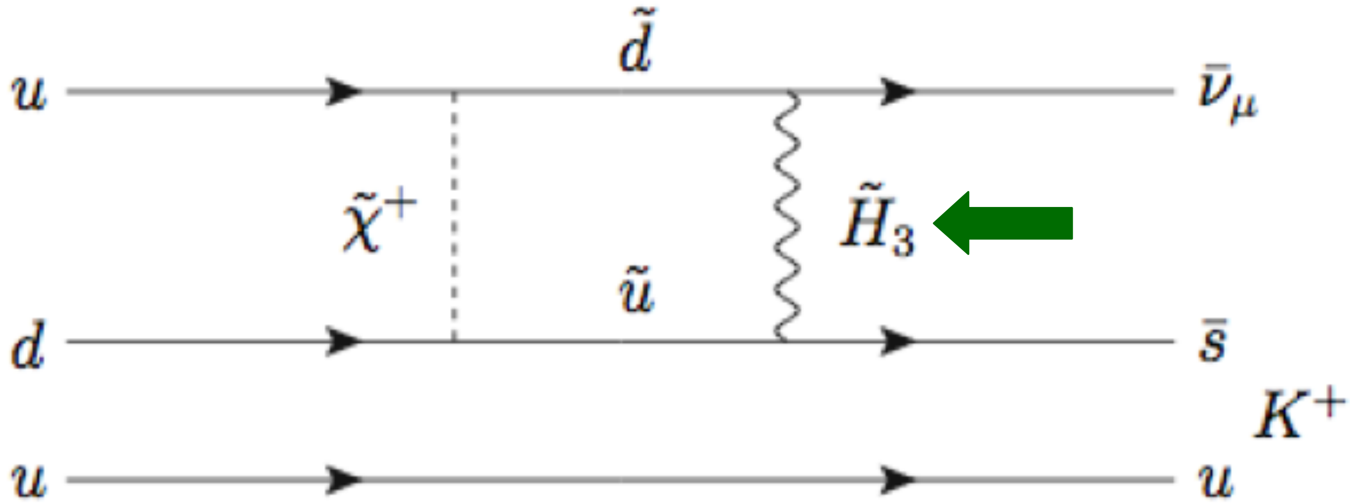


Proton lifetime expectations
(with caveats)



(Babu)

The decay mode $p \rightarrow \overline{\nu} + K^{+}$ is greatly enhanced in supersymmetric GUTS due to colored Higgsino exchange.



This decay mode is particularly suited for study by a LAr detector.

In a water Cerenkov detector, this mode is harder to detect.

But a water Cerenkov detector
has the edge for $p \rightarrow e^{+} + \pi^{0}$.

As for supernova neutrinos,
the detectors are complementary.

New Capabilities

When a new facility is built that provides capabilities we did not have before, we may well discover very interesting new physics that is not the physics the facility was built to look for.

Examples —

- ❖Homestake Solar Neutrino Experiment
- ❖IMB
- ❖Kamiokande
- ❖Super-Kamiokande

Conclusion

Large underground detectors could carry out a rich, broad program addressing deep scientific questions.